

Title: BSM Theory

Speakers: Tiann-Tevong You

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URL: <https://pirsa.org/23060078>

TEVONG.YOU@KCL.AC.UK

SUMMARY

• SM is an EFT

$$\begin{aligned} \mathcal{L}_{SM}^{EFT} = & \bar{\Psi} i \gamma^\mu D_\mu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + (D_\mu H)^\dagger (D^\mu H) + (y H \bar{\Psi}_L \Psi_R + h.c.) \\ & + \sum_{n=5}^{\infty} \sum_{\mathcal{O}_n} \frac{C_n^{in}}{\Lambda^{n-4}} \mathcal{O}_n^{in} + \mathcal{L}_{NP}^{light} \end{aligned}$$

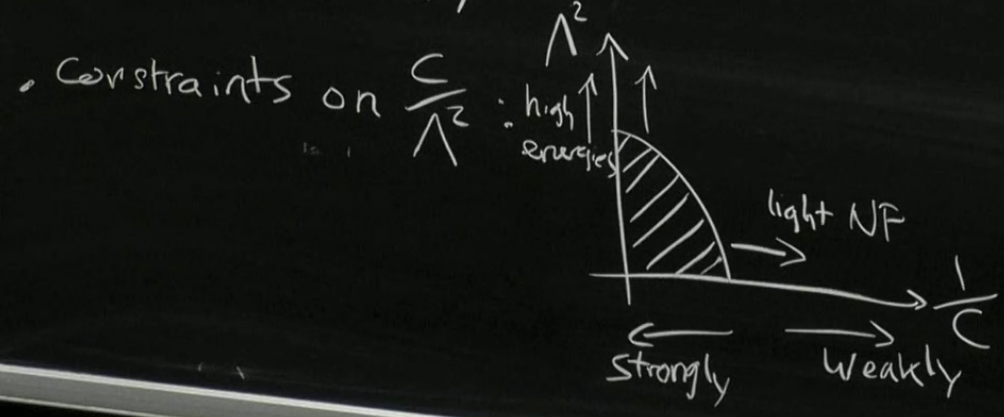
$\Lambda =$ cut-off scale

$C =$ Wilson coefficients (dimensionless)

Why $\frac{c_n}{\Lambda^{n-4}}$? $S = \int d^4x \mathcal{L}$ $t_h = c = 1$ $[S] = 0$ $[d^4x] = M^{-4} \Rightarrow [\mathcal{L}] = M^4$

$$\mathcal{L} = \overline{\Lambda^4} + M^2 \theta^{(2)} + M \theta^{(3)} + y \theta^{(4)} + \frac{1}{M} \theta^{(5)} + \dots$$

\uparrow cosmological constant $(10^{-3} \text{ eV})^4$ \uparrow Higgs mass



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$$\begin{aligned} \mathcal{L}_{SM}^{EFT} = & \bar{\Psi} i \gamma^\mu D_\mu \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\Theta_0}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^{\mu\nu a} G^{\rho\sigma b} \\ & + (D_\mu H)^\dagger (D^\mu H) + (y H \bar{\Psi}_L \Psi_R + h.c.) \\ & + \sum_{n=5}^{\infty} \sum_{\mathcal{O}_n} \frac{C_n^{in}}{\Lambda^{n-4}} \mathcal{O}_n^{in} + \mathcal{L}_{NP}^{light} + \mathcal{L}_{DM} \end{aligned}$$

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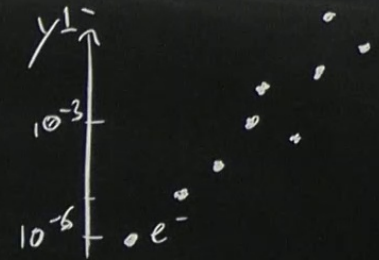
$C =$ Wilson coefficients (dimensionless)

• Problems of the SM

• Aesthetic: yukawas, flavour structure, put in hand

• Higgs potential is arbitrary

• Cancellations:



CAUTION

BE CAREFUL TO AVOID THE BRUSHING BOARD,
WHICH IS LOCATED AT THE BOTTOM OF THE BOARD.
IT IS RECOMMENDED BY AGENCY
FOR SAFETY PREVENTIVE MEASURES.
PLEASE PROCEED CAREFULLY.

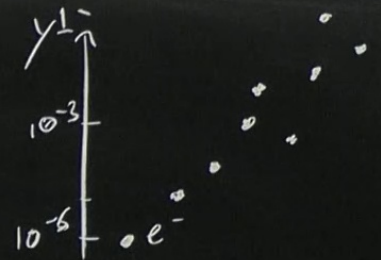
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• Theory breakdown:



CAUTION

BE CAREFUL TO AVOID THE BOARD, WHEN WORKING AT THE BOARD

IT IS PROHIBITED TO SMASH ANY OBJECTS AGAINST THE BOARD

PLEASE PROTECT YOURSELF

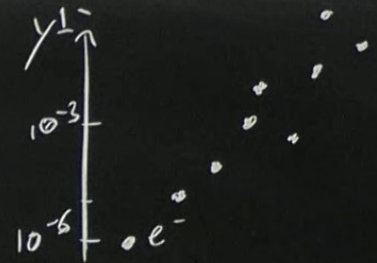
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Th: BH information paradox,



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Th: BH information paradox, QG

• Science is removing arbitrariness from explanations of natural phenomena

• Principle, not practicality



economy of principles



limitations of technology

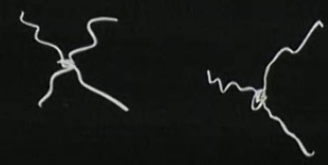
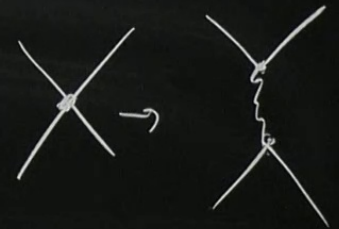
$$F = ma$$

• m inertia \leftrightarrow equivalence principle

g gravity

• Fermi theory: universality, V-A, put in hand

• Gauge theories \rightarrow single parameter



- Everything about the Higgs is arbitrary: parametrisation c.f. Condensed matter Higgs
- Expect Higgs sector to be calculable in underlying UV theory
- What is the microscopic origin of the Higgs?
- Such a theory has a calculable Higgs mass e.g.

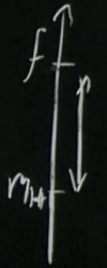
Composite Higgs: $V(H) \approx -\alpha f^2 \sin^2\left(\frac{H}{f}\right) + \beta f^2 \sin^4\left(\frac{H}{f}\right)$

$m_H^2 = 8 \left(\frac{\alpha}{2\beta}\right) \left(1 - \frac{\alpha}{2\beta}\right) \beta$ $\ll 1$

Supersymmetry: $m_{H_u}^2 \sim M_{\tilde{t}}^2 \sim (m_{H_u}^2 + |\mu|^2)$

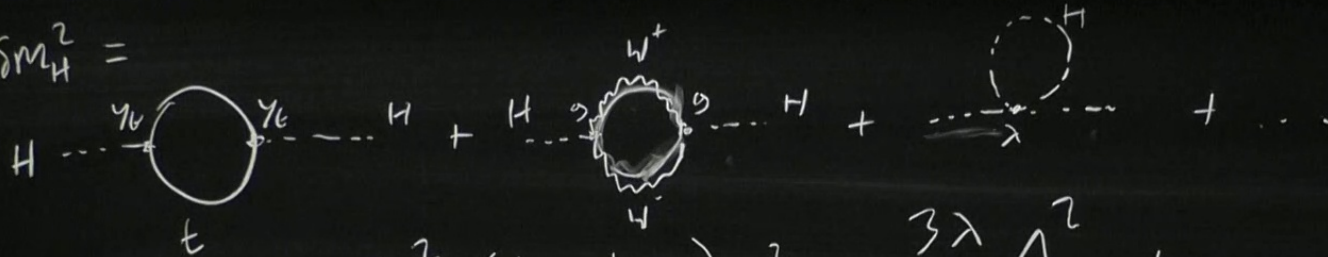
$\mu \lesssim 200 \text{ GeV}$ $m_{\tilde{t}}^2 \lesssim 400 \text{ GeV}$
for 10%

$\delta m_{H_u}^2(\tilde{t}) = -\frac{3Y_t^2}{4\pi^2} M_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$



• Sensitivity of M_H^2 to Λ^2 is a general consequence of symmetries

$$\delta M_H^2 =$$



$$\sim \frac{3y_t^2}{4\pi^2} \Lambda^2 - \frac{3g^2}{8\pi^2} \left(\frac{1}{4} + \frac{1}{8\cos^2\theta_W} \right) \Lambda^2 - \frac{3\lambda}{8\pi^2} \Lambda^2 + \dots$$

$$M_H^2 \text{ exp.} = M_H^2 \text{ bare} + \delta M_H^2$$

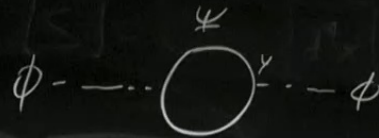
$$\Delta = \frac{\delta M_H^2}{M_H^2} \sim \left(\frac{\Lambda}{450 \text{ GeV}} \right)^2$$

↑ in SM Higgs mass is just a independent parameter

Independent of regularisation

e.g. dim. reg.

$$t = c = 1$$



$$\Lambda \sim m_\Psi \uparrow \quad \mathcal{L}^{UV} = i\bar{\Psi}\gamma^\mu \partial_\mu \Psi - M_\Psi \bar{\Psi}\Psi + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 - y\bar{\Psi}\Psi\phi$$

$$m \uparrow \quad \mathcal{L}_{\text{EFT}} = -\frac{1}{2} \left[m^2 + \frac{y^2}{4\pi^2} \left(1 - 3 \log \frac{M_\Psi^2}{\mu^2} \right) M_\Psi^2 \right] \phi^2$$

't-Hooft: "technical" naturalness: if a symmetry is restored when a parameter goes to zero then it is technically natural for that parameter to be small.

• Light fermion coupled to heavy scalar:

$$\delta m_\psi = m_\psi \left(\frac{3}{4} - \frac{3}{2} \ln \left(\frac{M_\phi^2}{\mu^2} \right) + \dots \right) \propto m_\psi$$

• Pions: $M_{\pi^0} = 135 \text{ MeV}$ $M_{\pi^\pm} = 140 \text{ MeV}$

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} M_\pi^2 (\pi_0^2 + \pi_1^2 + \pi_2^2)$$

light fermion coupled to heavy scalar:

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$$\delta m_\Psi = m_\Psi \left(\frac{3}{4} - \frac{3}{2} \ln \left(\frac{M_\phi^2}{\mu^2} \right) + \dots \right) \propto m_\Psi$$

Pions: $M_{\pi^0} = 135 \text{ MeV}$ $M_{\pi^\pm} = 140 \text{ MeV}$

$$\mathcal{L}_m = \frac{1}{2} M_\pi^2 (\pi_0^2 + \pi_1^2 + \pi_2^2)$$

$$\mathcal{L}_{k.m} = \frac{1}{2} (\partial_\mu \pi_0)^2 + \left| (\partial_\mu + i e A_\mu) \pi_\pm \right|^2$$

$$\delta \mathcal{L}_{\text{mass}} \sim \frac{e^2}{(4\pi)^2} \Lambda^2 \pi^+ \pi^-$$

↑ breaks shift symmetry

$$\Lambda \sim 750 \text{ MeV}$$

$\Rightarrow \rho$ meson, a_1 meson